Feasibility of using mobile air cleaners in school classrooms to remove respiratory aerosols

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Abstract. To investigate the feasibility of using mobile air cleaners (MACs) in school classrooms for reducing respiratory aerosols, a test on aerosol removal of seven different types of MACs was conducted in a university classroom, for the optimal condition determined by a prior experimental study. Most of the MACs achieved a good level of clean air delivery rate (CADR) (900-1000 m^3/h), and the CADR increased with the number of devices used. Based on the results, three MACs were further selected for conducting an ongoing field study in 45 classrooms at five Dutch primary schools. Each classroom was assigned one type of MAC with two devices, and was monitored for a period of six weeks with three weeks the devices turned on and three weeks off. The assessments of feasibility are based on measurements of indoor air quality, information on absenteeism of the pupils, and interviews with the occupants. The results are yet to be collected to draw further conclusions. However, problems were already encountered during the installation process of the devices which hindered the realization of the pre-determined strategies.

1 Introduction

Airborne transmitted pathogen-laden respiratory particles, also called respiratory aerosols, is the primary cross-infection route of respiratory infectious diseases such as COVID-19 [1]. Such aerosols are released when people breathe, speak, cough, or sneeze. School classrooms are often with a dense occupancy and long-occupied hours per day, and thus are of high risk for cross-infection to take place [2]. To tackle such problem, mobile air cleaners (MACs) have been proposed to be adopted as a supplementary solution for school classrooms with limited ventilation [3].

Hence, in our prior study [4], a comprehensive assessment was conducted on different types of MACs, to provide reference for practical usage. To do so, firstly 152 products were pre-selected after screening more than 300 products found in the market. Categorization and comparison were then made based on the technical specifications of the products, considering the feasibility and affordability. Eventually, seven types of MACs were selected for further assessments, which covered different combinations of air cleaning technologies, induced airflow patterns, fan capacities, and dimensions. Accordingly, they were tested for different settings (i.e. fan levels) and configurations (including location and number of devices), in the Experience room of SenseLab at Delft University of Technology [5], which is of half size of a classroom (70 m^3), and with a typical classroom interior setting. The assessments included: 1) an aerosol decay test: the time evolution of aerosol concentration was monitored after filling the room with aerosols generated by a specific spraying technique, to calculate the aerosol removal rate and clean air delivery rate (CADR), and 2) a panel perception test: a panel of subjects was recruited to assess noise and air movement generated by the MACs, combined with measurements of sound pressure level and air velocity. Based on the results, the optimal condition of each type of MAC was determined, with sufficient clear air and an acceptable noise level.

As follow-up of [4], this study is aimed at investigating the feasibility of using the selected MACs in real classrooms. Firstly, they were tested in a real classroom at the university, and from there three were selected for a field study carried out in Dutch primary schools.

2 Test in a real classroom

2.1 Methods

An aerosol decay test was conducted in a classroom at the Faculty of Architecture and the Built Environment of Delft University of Technology, during July 2023. The classroom has a volume of 139 m^3, with six openable windows and one door. The classroom is equipped with a mechanical ventilation system with air supplies on both sides and an air exhaust in the middle of the ceiling. During the test, the windows and door were closed, while the mechanical ventilation was kept on. The procedure of the test was the same as performed in the lab study [4], with the same instruments and setup. An aerosol generator developed by [6] was used to continuously spray aerosols into the room during the build-up phase. Once the room was filled with aerosols, the aerosol generator was turned off and the MACs were turned on, to start the decay phase. The decay phase ended when the concentration of aerosol decreased to a relatively low level (< 5 μg/m³). The concentrations of $PM_{2.5}$ and PM_{10} were monitored by six NOVA SDS011 PM sensors, which were evenly distributed in the room on six tables. One natural decay test was also performed without any MAC operating.

As previously mentioned, for each MAC one condition was tested based on the results of the experimental study [4], as specified in **Table 1**. All the MACs were tested at the highest setting, except for MAC7, which was tested at a low setting.

Table 1. Conditions of the aerosol decay test of the mobile air cleaners.

Device	Number of devices	Setting	Location
MAC1	2	10	Diagonally at 2 corners
MAC2	4	2	4 corners
MAC3	4	4	4 corners
MAC4	2	2	Diagonally at 2 corners
MAC5	1	5	Centre of front wall
MAC6	2	8	Diagonally at 2 corners
MAC7	2	4	Diagonally at 2 corners

The aerosol removal rate and CADR of the MACs were also calculated according to the methods used in [4]. The total decay and natural decay curves were described as equation (1):

$$C(t) = C_\infty + (C_0 - C_\infty)e^{-kt},\ k = k_{total} \text{ or } k_n \quad (1)$$

Where:

- C is the aerosol concentration [μg/m³]
- t is the time after the decay process starts [h]
- C_0 is the aerosol concentration when $t = 0$ [μg/m³]
- C_∞ is the aerosol concentration when $t >> k^{-1}$ [μg/m³]
- k is the decay coefficient [h^{-1}]
- k_{total} is the coefficient of the total decay, here also the total aerosol removal rate [h^{-1}]
- k_n is the coefficient of the natural decay [h^{-1}]

The aerosol removal rate of the MACs k_{mac} [h^{-1}] and CADR [m³/h] were then calculated using equation (2) and (3):

$$k_{mac} = k_{total} - k_n \quad (2)$$

$$CADR = k_{mac} \times room\ volume \quad (3)$$

2.2 Results and discussion

The results of CADR of the tested MACs are presented in **Fig. 1**, for both $PM_{2.5}$ and PM_{10}. The minimum amount of ventilation ("clean" air) required by the Dutch Building Decree [7] in school classrooms is 8.5 l/s/p, while the recommended amount of ventilation for a good IAQ is 10 l/s/p [8]. Assuming a student occupancy of 30 persons, then the range of CADR is 918-1080 m³/h, as marked in the figures. For $PM_{2.5}$, the CADR of MAC4 and MAC6 reached the minimum requirement, while MAC2 and MAC3 exceeded the recommended level. For PM_{10}, the CADR of MAC5 passed the minimum requirement, while MAC2, MAC3, MAC4, and MAC6 were all above the recommended level. Among all the MACs, MAC1 always showed the lowest amount of CADR, which was possibly due to the horizontal design of the air supply, and thus the clean air could not be effectively diffused throughout the room. Therefore, such MAC is not ideal for school classrooms. For MAC2 to MAC6, although similar results were found in the lab test [4], in the real classroom the MACs tested with four devices, i.e., MAC2 and MAC3, showed much higher CADR than the others, while the one tested with one device, i.e., MAC5, was much lower than the others, and the two tested with two devices, i.e., MAC4 and MAC6, were in between. This indicates the necessity of using multiple devices when the room size increases. Nevertheless, according to the results of the panel perception test conducted in [4], both MAC2 and MAC3 generated very loud noise which exceeded far beyond the limited level (35 dB(A) prescribed in [9]), and was considered to be not acceptable by the subjects, whereas MAC4 and MAC6 produced less noise and were more acceptable, and thus were more suitable to be used in practice. In addition, as MAC7 was tested at the low setting, the noise level was well below the limit, yet a CADR around 800 m³/h was still reached in the real classroom, which was thus suggested for use in practice as well.

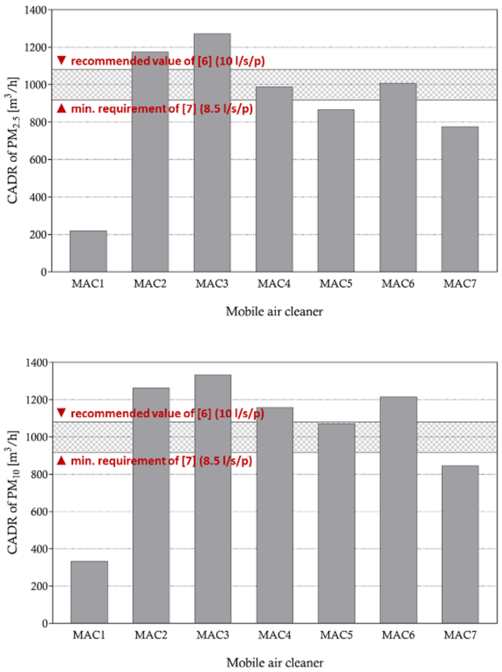

Fig. 1. CADR of $PM_{2.5}$ (above) and PM_{10} (below) of the tested mobile air cleaners in the classroom. The minimum requirement and recommended value were calculated based on the assumption of a student occupancy of 30 persons.

Moreover, compared to the results of the lab test [4], in the real classroom the CADR of all the MACs were found to be increased by 10% to 47%, for both $PM_{2.5}$ and PM_{10}, expect for MAC1. This could be due to the mechanical ventilation present in the classroom, which helped mixing the air during the decay phase, and most likely accelerating the aerosol removal, as k_n was found to have increased by 1.36 times compared to k_n in the lab. This indicates the potential of combining mechanical ventilation and MACs in school classrooms for a better aerosol removal.

It is also worth noting that this test was performed during summertime, while in real life the MACs are more often needed during the heating season, when natural ventilation in school classrooms is limited, and the incidence of respiratory infectious diseases is in general higher [10]. Since the change in outdoor air temperature and relative humidity greatly affect the indoor air conditions, whether the MACs can maintain steady performance during different seasons remains unclear. Moreover, the change in indoor and outdoor air temperature and relative humidity can also affect occupants' perception of the MACs [11]. Therefore, to better examine the feasibility of the proposed strategies for using MACs in school classrooms, further investigations are needed.

3 Field study

3.1 Methods

Following the studies conducted in the lab and the university classroom, a field study was carried out in November and December 2023. Five primary schools in Roermond (noted as School1 to School5), a city located in the south-east of the Netherlands, were enrolled in this study on a voluntary basis. The location of the selected schools is shown in **Figure 2**. Among the five schools, School1 has eight classrooms, School3 has ten classrooms, and the rest have more than ten classrooms. Therefore, for School1 and School3, all classrooms were involved in this study, while in other schools nine classrooms were selected, which resulted in 45 classrooms in total. The selected classrooms cover all ages groups of pupils at the schools (5-12 years old), and were coded from 1 to n (n is the number of classrooms selected in each school). On average nine classrooms were selected at each school for applying the MACs. The selected classrooms cover all ages groups of pupils at the school (5-12 years old), with a typical occupancy of 20-25 persons. The classrooms are of a similar floor area of 45-50 m^2, and have multiple openable windows for natural ventilation. Some classrooms are also equipped with mechanical ventilation systems.

Figure 2. Location of the selected primary schools (adapted from Google Maps, 2024).

According to the results of the prior tests, three MACs, namely MAC4, MAC6, and MAC7, were selected to be applied in the selected classrooms. In School1, two classrooms were assigned with MAC7, three were assigned with MAC4 , and three with MAC6. In School3, four classrooms were assigned with MAC7, three with MAC4, and three with MAC6. In the other schools, the three types of MACs were evenly assigned among the nine classrooms. The distribution of MACs among the classrooms was determined on a random basis, and each classroom with two devices, as determined in the prior tests.

During the first week of November 2023, the schools were visited, and the MACs were brought inside the classroom. The researchers inspected the room to determine the optimal location of the devices, considering multiple factors such as the induced airflow pattern of the MACs, the air distribution in the room, the actively space of the pupils and teachers, and the availability of sockets, etc. For MAC4 and MAC6, it is suggested to operate at the maximum setting, while for MAC7 it is suggested to use the low setting, as specified in **Table 1**. Instructions on how to switch on/off the devices and how to set them to the suggested settings were provided on each device by the researchers.

Starting from the second week of November 2023, the field study lasted for six weeks, which consisted of two periods of three weeks with the MACs being turned ON and OFF, respectively. School1, School4, and School5 the MACs started with the ON period, where the school directors and teachers were instructed to turn on/off the devices at the beginning/end of each school day during the first three weeks. Then the MACs were turned off for three weeks. For School2 and School3 it was performed in the opposite manner, with three weeks OFF followed by three weeks ON.

During this six-week period, the concentrations of $PM_{2.5}$ and PM_{10} were continuously monitored in three classrooms equipped with the three different MACs per school, using one NOVA SDS011 PM sensor, usually placed nearby the teacher's table. CO_2 and TVOC concentrations were also monitored simultaneously, using an MH-Z19B and an SGP30 sensor, respectively. The logging interval was 5 min. Besides, the teachers were asked to complete a compliance questionnaire about their operation of the MACs (e.g., turning on/off, changing settings, moving location, etc.) as well as the windows (open/close). In the meantime, interviews with pupils and teachers were conducted regarding their perception of the use of MACs in the classrooms. Information on the absenteeism of the pupils in the selected classrooms were also collected for the monitored period.

3.2 Preliminary results and discussion

While the data is still being analysed, already some phenomena regarding the feasibility of using MACs in the school classrooms were observed. Firstly, most of the classrooms were quite crowded and cluttered, leaving limited space for placing the MACs. Thus, in some cases it was not possible to place the devices on the planned spots, e.g., the two devices could not be diagonally facing each other, or had to be located somewhere far from the occupied area. Secondly, limited number of power supplies/sockets were found in many classrooms, and thus extension cords and splitters were needed to properly plug in all the electronic devices in the room. Thirdly, some questionnaire and the interview already showed that many teachers found the presence of the MACs inconvenient for their movement during the lessons. In some classrooms, the pupils and teachers found the MACs too noisy or draughty, and thus they lowered the setting or turn the devices off. In general, pupils showed a more positive attitude towards the use of MACs in the classrooms than the teachers, as they were enthusiastic about the new things, while the teachers were more reluctant to any changes in their workplace.

Nonetheless, the preliminary results of the indoor air quality measurements indicated that the selected MACs can effectively reduce the particle concentration in the classrooms regardless of the source, as both $PM_{2.5}$ and PM_{10} concentrations in most of the monitored classrooms were found to be lower during the ON period than the OFF period. Further analysis will be done to examine the significancy of the differences. On the other hand, CO_2 and TVOC concentrations did not show much difference with the MACs on or off in the classrooms.

4 Conclusions

In this study, seven MACs were tested in a university classroom for their performance of aerosol removal, for the pre-determined conditions. The results aligned with the prior experimental study and indicated the applicability of using MACs in real classrooms. It is concluded that to efficiently reduce the aerosol concentration, at least two MACs are needed per classroom. The devices should be placed diagonally in the room, one in the front and one in the back. To obtain a sufficient amount of CADR, most of the devices should be operated at the maximum setting, where then the risks of noise and draft should be carefully considered.

Based on the test three MACs were further selected and were applied into 45 classrooms at five Dutch primary schools. Limited space and sockets were encountered in many classrooms, and thus desired location of the MACs was not always possible. Although preliminary results were positive with respect to effective particle removal by the selected MACs in the classrooms, operating the MACs continuously at the maximum setting may not be feasible, as the noise and draft generated led to unacceptable discomfort to the occupants, in particular during the heating season. Hence, the pre-determined strategies might need to be adjusted to ensure better usage of MACs in school classrooms. Still, more conclusions and recommendations are yet to be drawn after the study is completed.

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